PRINCETON UNIVERSITY

SIMONS FOUNDATION

IAS INSTITUTE FOR ADVANCED STUDY

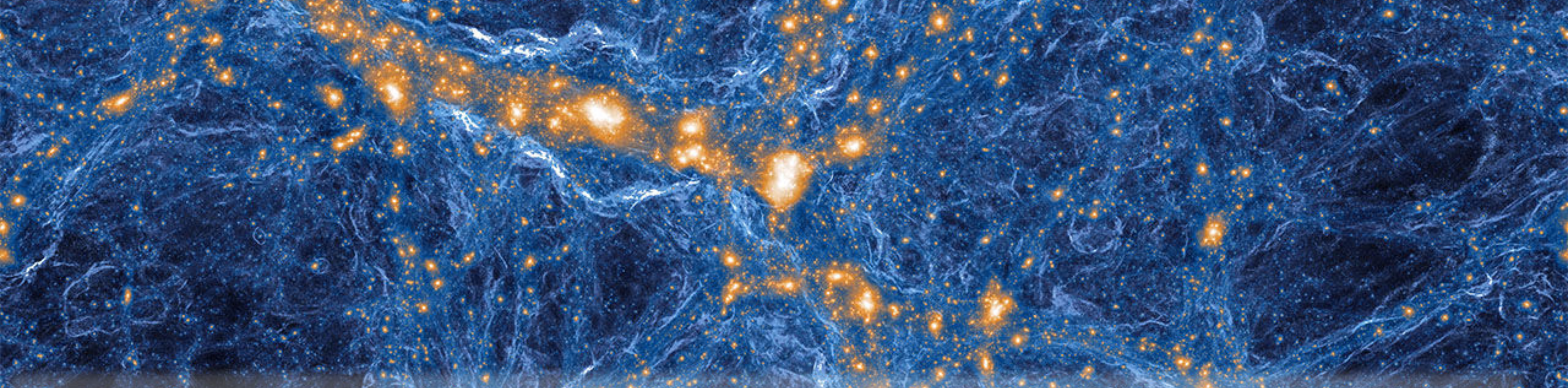
COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

CERN





(See also d'Amico, Senatore, Lewandowski, Zhang)



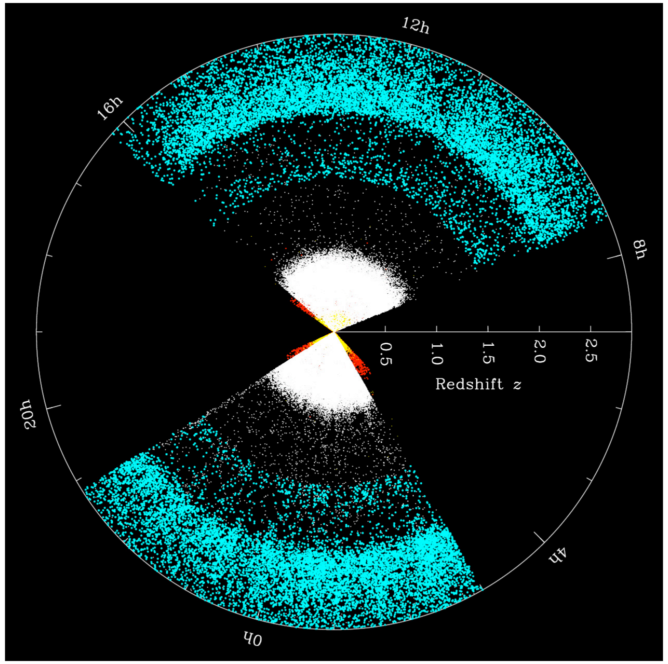
Constraining Inflation with BOSS DR12

Oliver Philcox (Columbia / Simons Foundation)

PNG Workshop, *September 2022*

Collaborators:
Mikhail Ivanov, Giovanni Cabass,
Marko Simonovic, Matias Zaldarriaga

FROM GALAXY SURVEYS TO INFLATION



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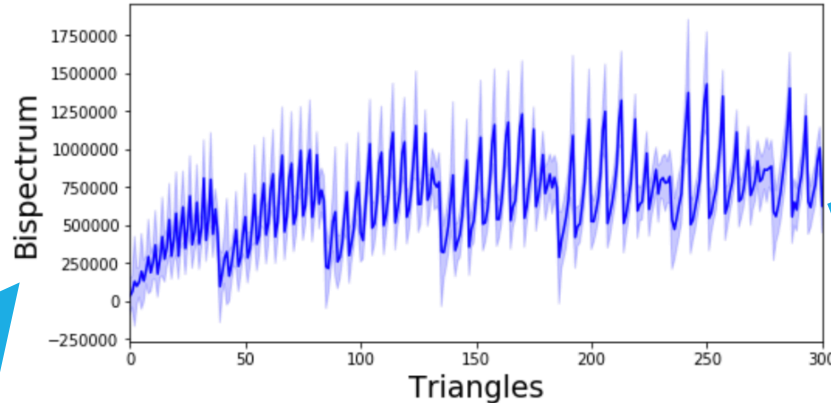

Theory model

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\begin{aligned}
Z_1(\boldsymbol{q}_1) &= K_1 + f\mu_1^2, \qquad\qquad (\text{A.3})\\
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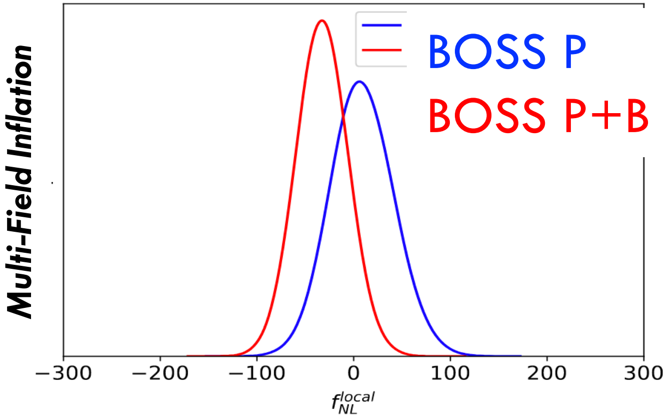


$f_{\rm NL}$ bounds

SDSS-III, **Philcox**+22, Cabass+22

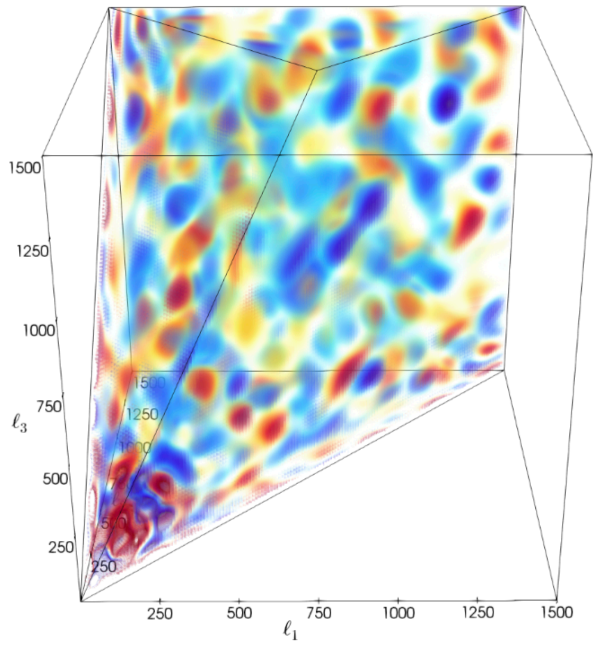
HOW CAN WE MEASURE $f_{\rm NL}$?

$$B_\zeta(\mathbf{k}_1, \mathbf{k}_2) \approx \frac{6}{5} f_{\rm NL} P_\zeta(k_1) P_\zeta(k_2) + 2 \text{ perms.}$$

1. **CMB Bispectrum**

See Will's talk!

Planck TTT Bispectrum



$f_{\rm NL}$ Constraints

Local	6.7 ± 5.6
Equilateral	6 ± 66
Orthogonal	−38 ± 36

≈ 2× better with CMB-S4!

Planck 2018 IX

HOW CAN WE MEASURE $f_{\rm NL}$?

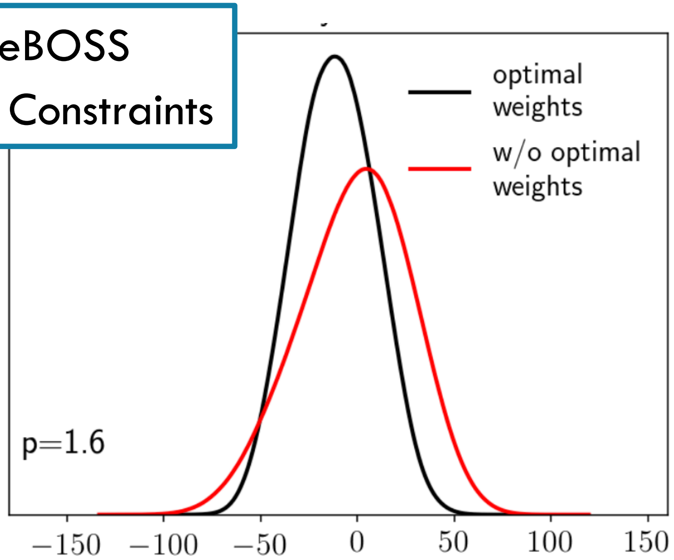
$$B_\zeta(\mathbf{k}_1,\mathbf{k}_2) \approx \frac{6}{5} f_{\rm NL} P_\zeta(k_1) P_\zeta(k_2) + 2 \text{ perms.}$$

1. CMB Bispectrum

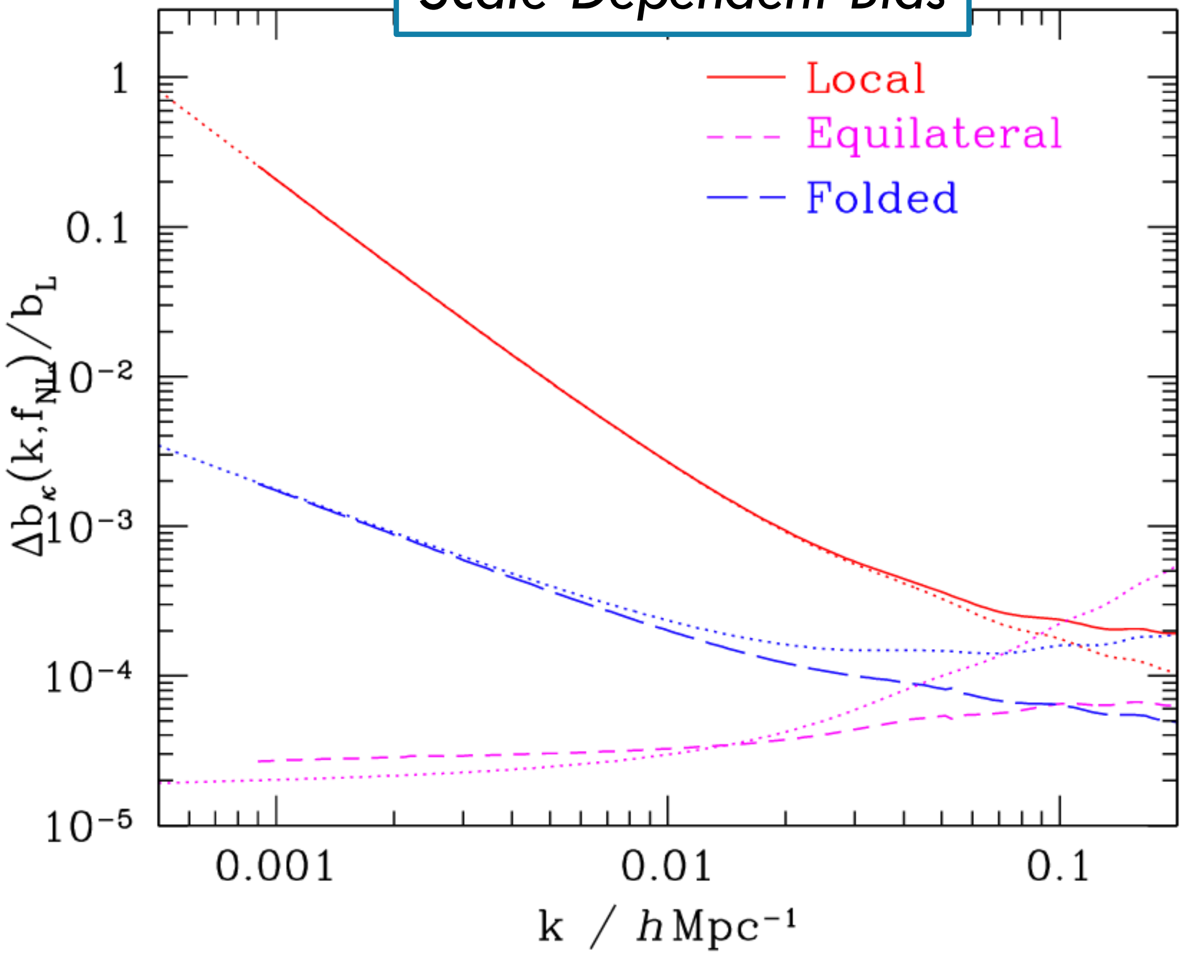
2. **Galaxy Power Spectrum**

See Eva-Maria and others' talks!

eBOSS $f_{\rm NL}^{\rm loc}$ Constraints



Scale-Dependent Bias



Desjacques & Seljak 10, eBOSS 21

HOW CAN WE MEASURE $f_{\rm NL}$?

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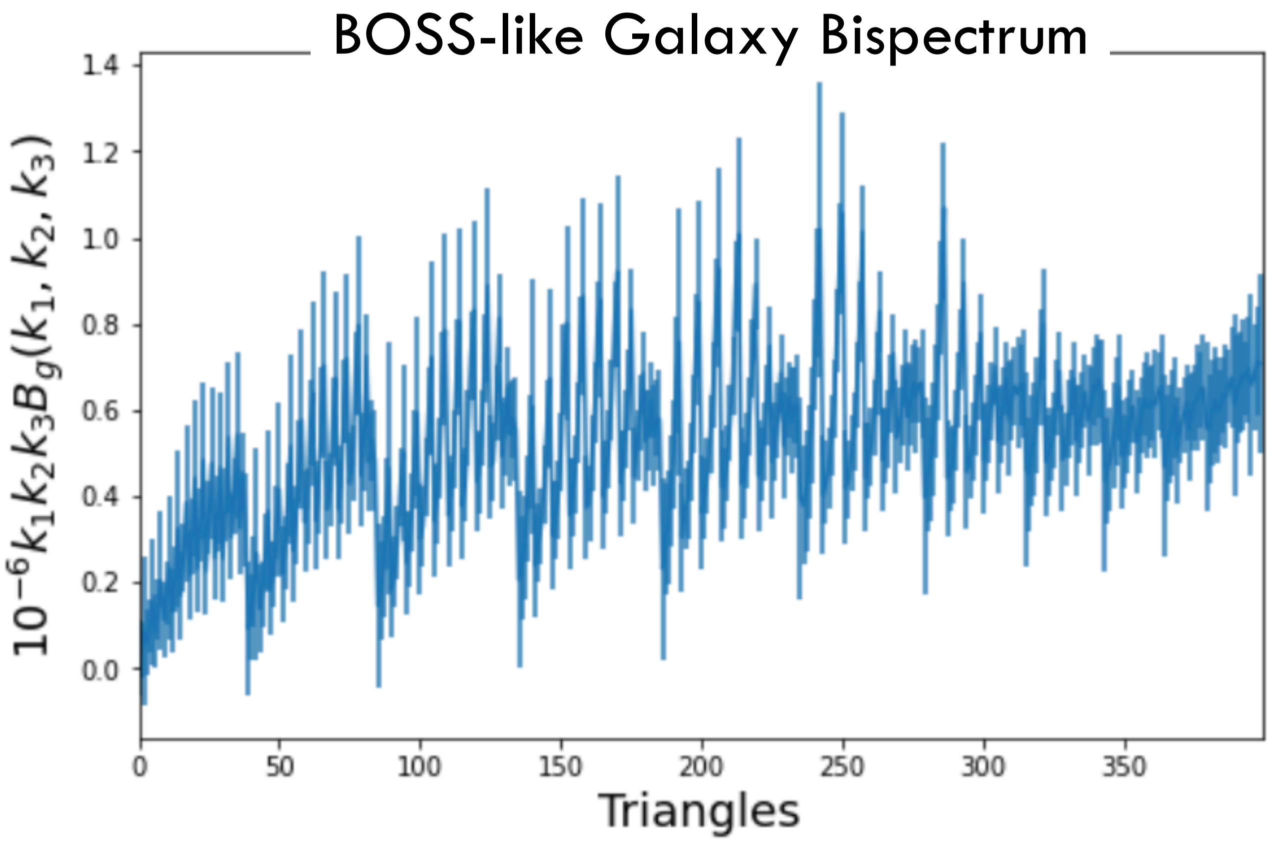
1. CMB Bispectrum
2. Galaxy Power Spectrum
3. **Galaxy Bispectrum**

See also Hector's talk!

We need a good theory model!



Philcox+21, Cabass+21,22

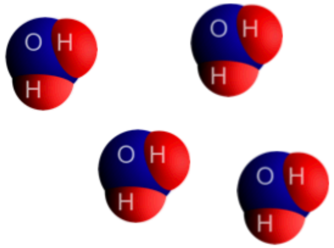
THE EFFECTIVE FIELD THEORY OF LSS

- **Analytic** theory for $\delta(\mathbf{x})$, based on the non-ideal **fluid equations**

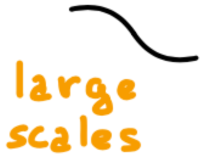
$$\dot{v}^i + H v^i + v^j \partial_j v^i = \frac{1}{\rho} \partial_j \tau^{ij}$$

- A <u>controlled</u> **Taylor series** in k/k_{NL}

(or $k\sigma_{\mathrm{FoG}}$, kR_{Halo})



- **Major Ingredient:** *Back-reaction* of small-scale physics on large-scale modes



e.g. Baumann, Carrasco, Assassi, Senatore, Zaldarriaga, etc.

MODELLING PNG

Theory model requires:

- Primordial bispectrum:

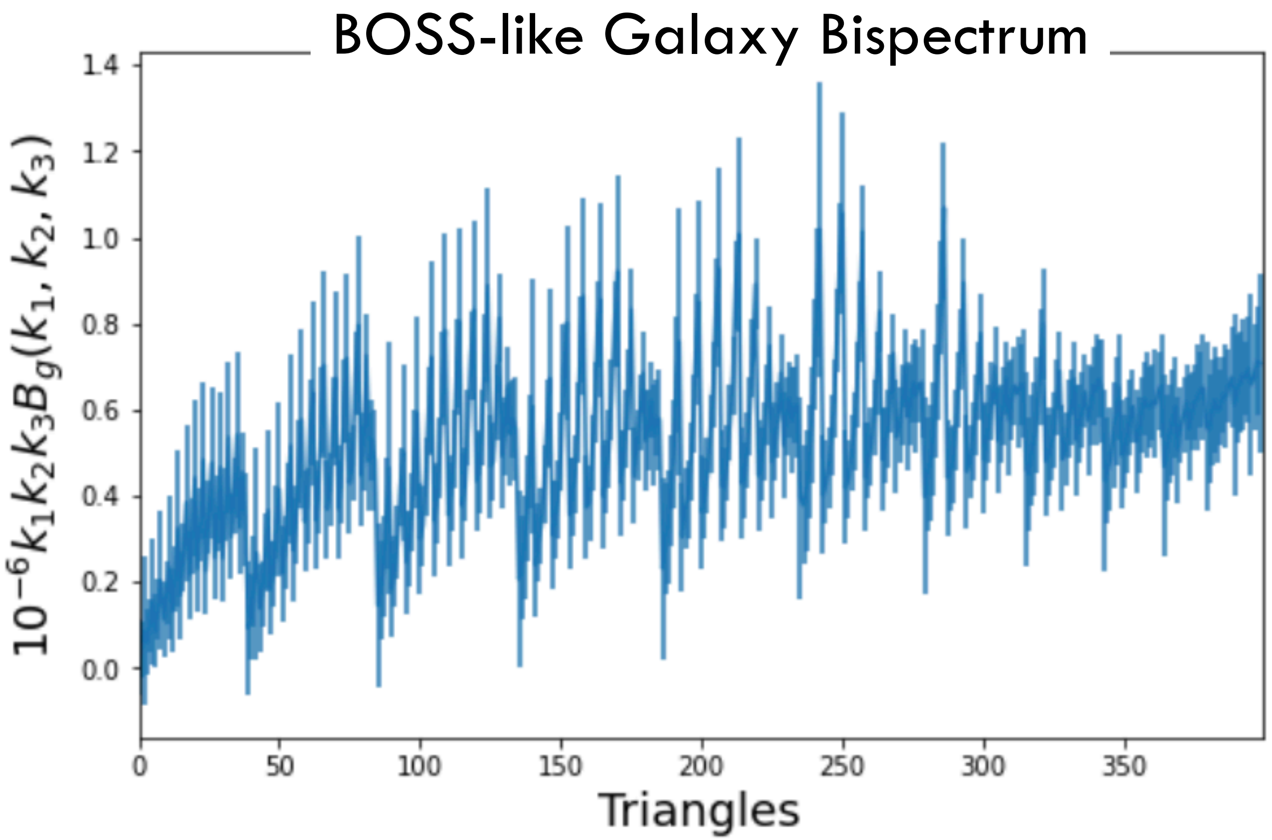
$$\langle \delta^{(1)} \delta^{(1)} \delta^{(1)} \rangle \sim f_{\rm NL} P^2(k)$$

- Scale dependent bias:

$$b_1(f_{\rm NL}) \to b_1 + (b_\phi f_{\rm NL})/k^2$$

- Loop corrections:

$$P_{gg}(\boldsymbol{k}) \to P_{gg}(\boldsymbol{k}) + f_{\rm NL} \int d\boldsymbol{q}\, \alpha\, P(\boldsymbol{q}) P(\boldsymbol{k}-\boldsymbol{q})$$

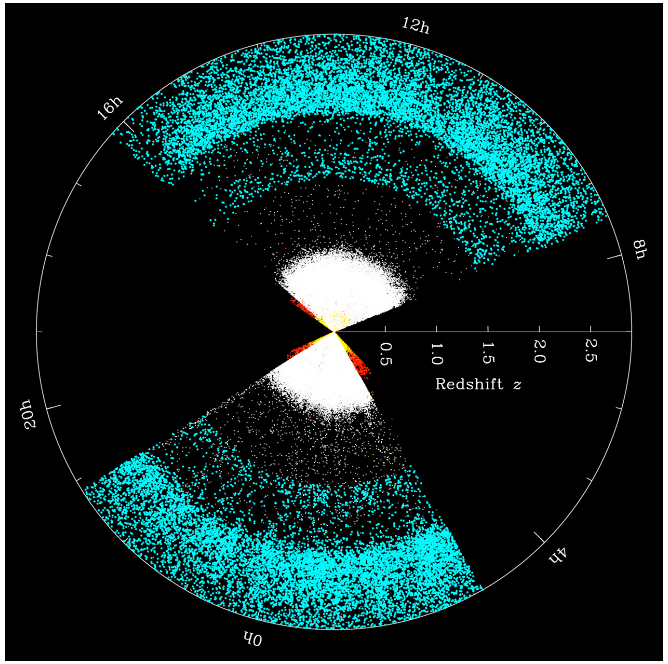


$$B_g = B_g(f_{\rm NL}^{\rm eq}, f_{\rm NL}^{\rm orth}, f_{\rm NL}^{\rm loc})$$

See GitHub.com/michalychforever/CLASS-PT

Cabass+21,22 (see also d'Amico+22)

FROM GALAXY SURVEYS TO INFLATION



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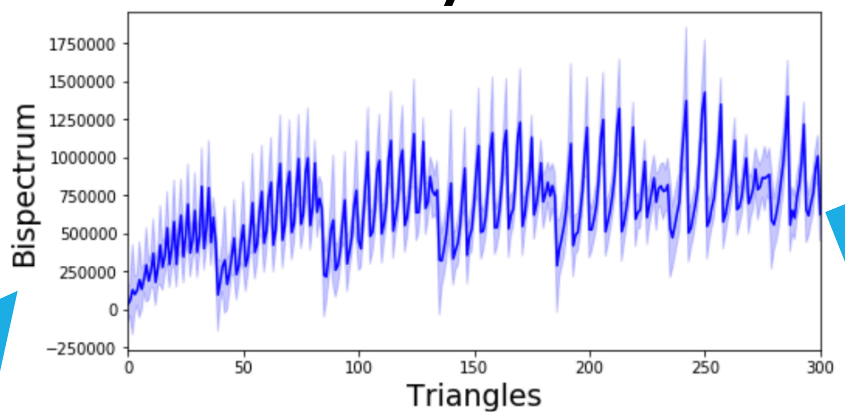

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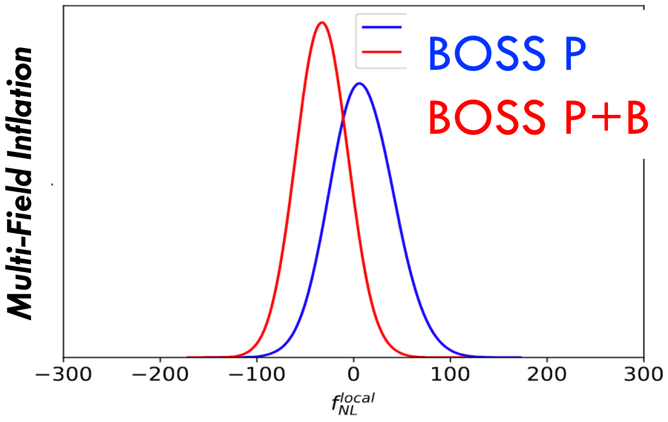


$f_{\rm NL}$ bounds

SDSS-III, Philcox+22, Cabass+22

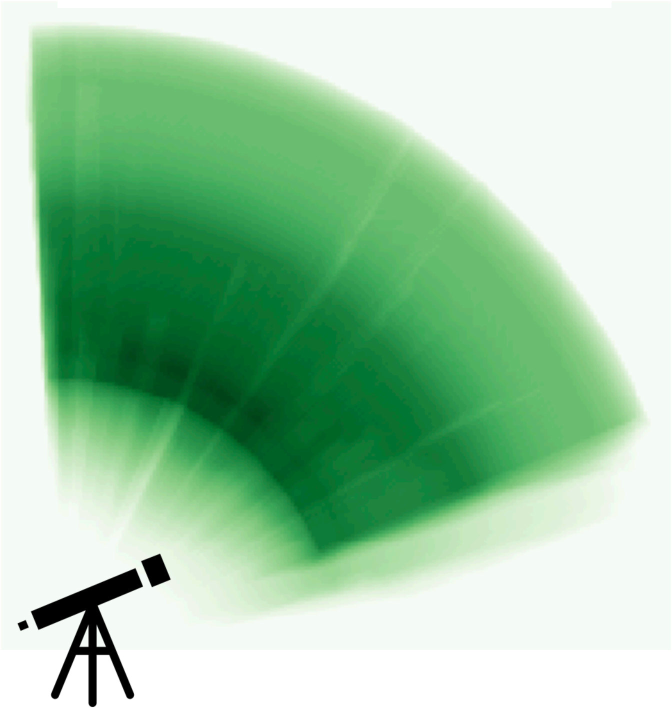
HOW TO MEASURE A BISPECTRUM

We usually measure the **window-convolved** bispectrum

$$B_g(\mathbf{k}_1,\mathbf{k}_2) \to \int_{\mathbf{p}_1\mathbf{p}_2} W(\mathbf{k}_1-\mathbf{p}_1)W(\mathbf{k}_2-\mathbf{p}_2)W(\mathbf{p}_1+\mathbf{p}_2-\mathbf{k}_1-\mathbf{k}_2)B_g(\mathbf{p}_1,\mathbf{p}_2)$$

Understanding this is **crucial** for getting robust $f_{\rm NL}$ bounds

Survey Mask, $W(\mathbf{r})$



Gil-Marin 16, **Philcox** 21 (see also Pardede+22)

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Understanding this is **crucial** for getting robust f_{NL} bounds

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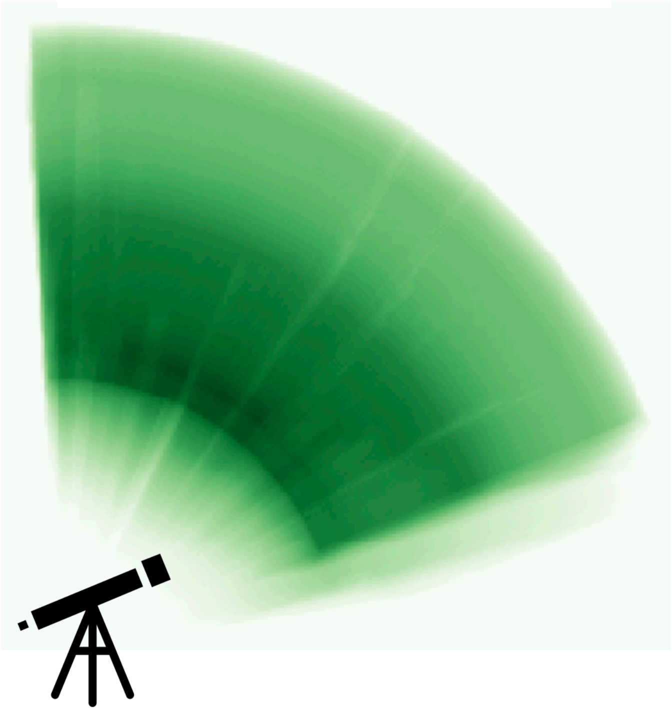


Three options:

1. Explicitly perform convolution integral *[very expensive!]*
2. Make approximations *[robust?]*
3. Circumvent the problem!

See Kevin's talk!

Gil-Marin 16, **Philcox** 21 (see also Pardede+22)

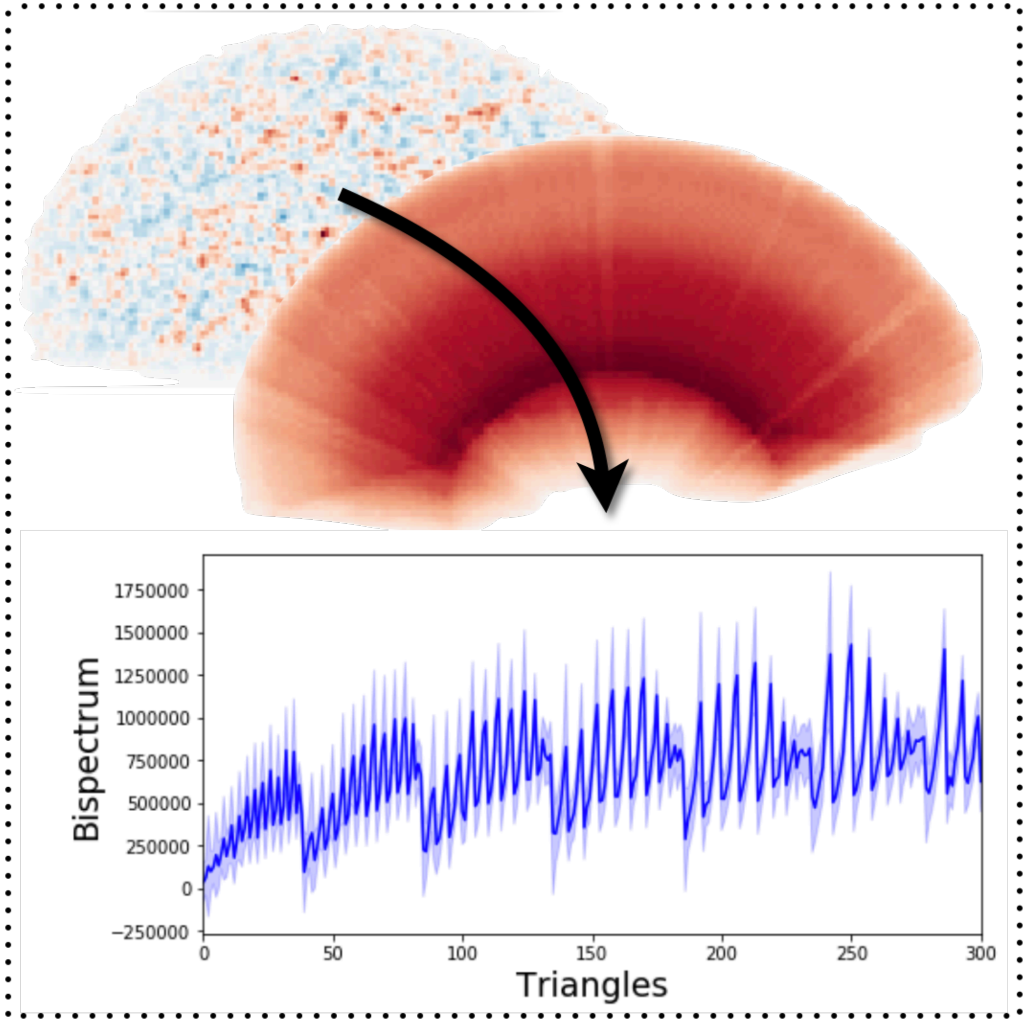
BISPECTRA WITHOUT WINDOWS

Estimate the **unwindowed** bispectrum directly

$$B_g^{\rm win}(\mathbf{k}_1,\mathbf{k}_2) = \int_{\mathbf{p}_1\mathbf{p}_2} W(\mathbf{k}_1-\mathbf{p}_1)W(\mathbf{k}_2-\mathbf{p}_2)W(\mathbf{p}_1+\mathbf{p}_2-\mathbf{k}_1-\mathbf{k}_2)B_g(\mathbf{p}_1,\mathbf{p}_2)$$

We use a **maximum-likelihood** estimator for the **true** bispectrum

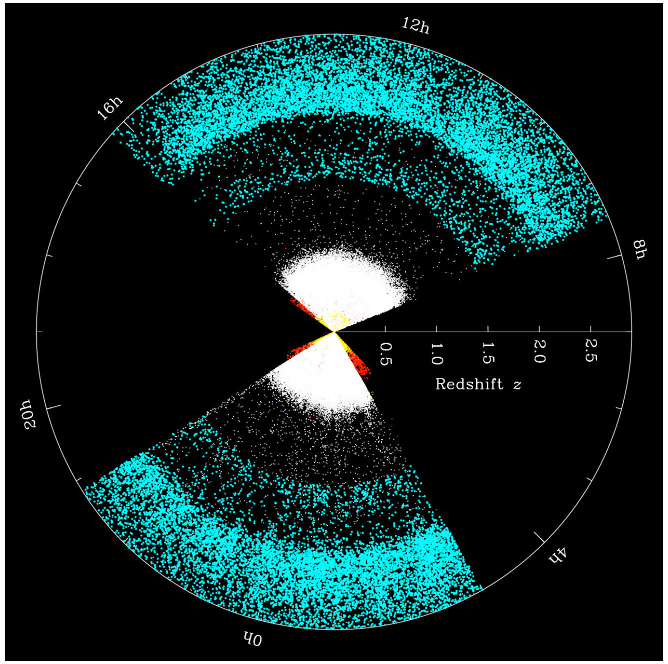
$$\nabla_{B_g} L[\text{data}|B_g] = 0 \quad \Rightarrow \quad \widehat{B}_g = \cdots$$



See GitHub.com/oliverphilcox/Spectra-Without-Windows

Philcox 20, 21

FROM GALAXY SURVEYS TO INFLATION



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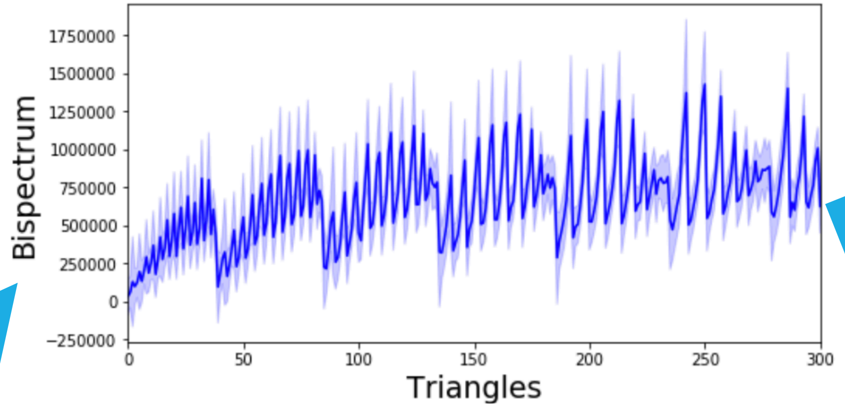

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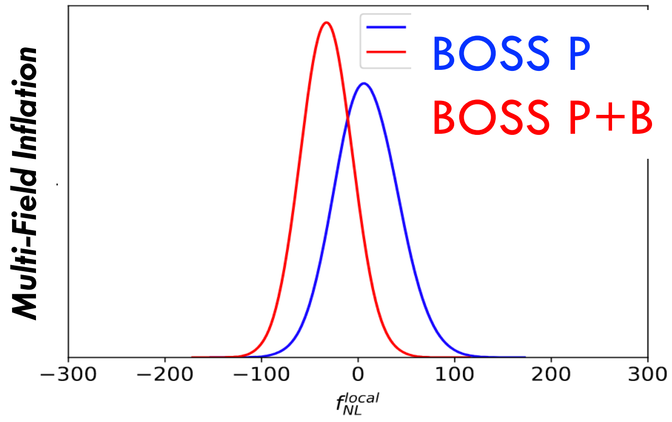
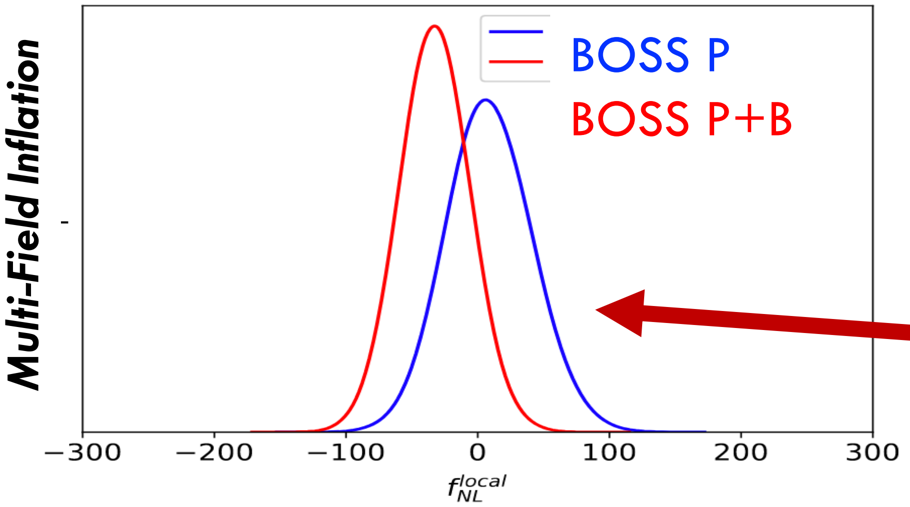


$f_{\rm NL}$ **bounds**

SDSS-III, Philcox+22, Cabass+22

CONSTRAINTS ON f_{NL}



BOSS Power Spectrum + Bispectrum + $O(f_{\mathrm{NL}})$ Theory Model

$$f_{\mathrm{NL}}^{\mathrm{local}} = -33 \pm 28$$

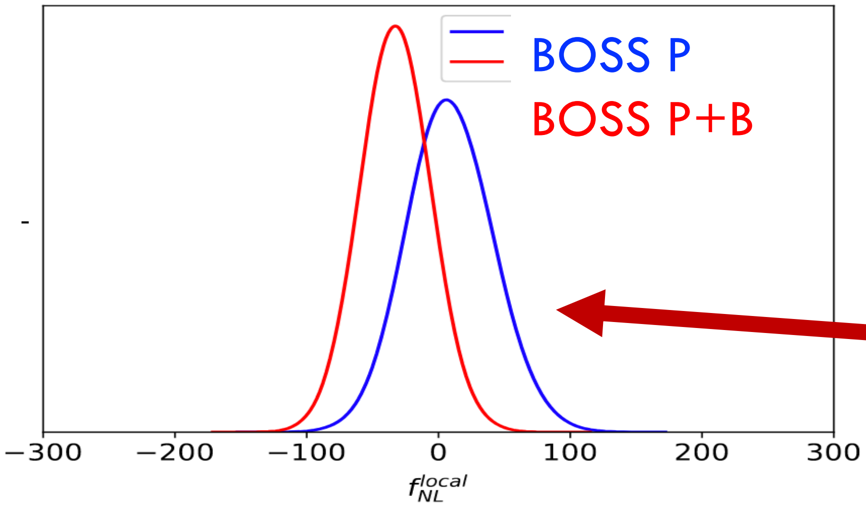
Really measuring $b_\phi f_{\mathrm{NL}}$ - see Alex's talk!

All analysis is public:
github.com/oliverphilcox/full_shape_likelihoods

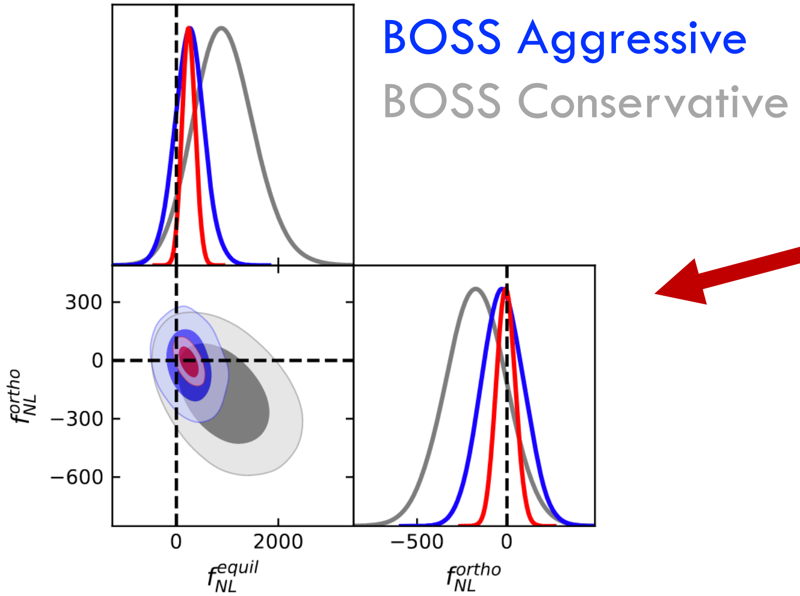
Cabass+21,22 (see also d'Amico+22)

CONSTRAINTS ON f_{NL}

Multi-Field Inflation



Single-Field Inflation



BOSS Power Spectrum + Bispectrum + $O(f_{\mathrm{NL}})$ Theory Model

$f_{\mathrm{NL}}^{\mathrm{local}} = -33 \pm 28$

Really measuring $b_\phi f_{\mathrm{NL}}$ - see Alex's talk!

$f_{\mathrm{NL}}^{\mathrm{equil}} = 260 \pm 300$

$f_{\mathrm{NL}}^{\mathrm{orth}} = -23 \pm 120$

- First measurement without CMB!
- Needs bispectrum!

All analysis is public:
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Cabass+21,22 (see also d'Amico+22)

CONSTRAINING INFLATION

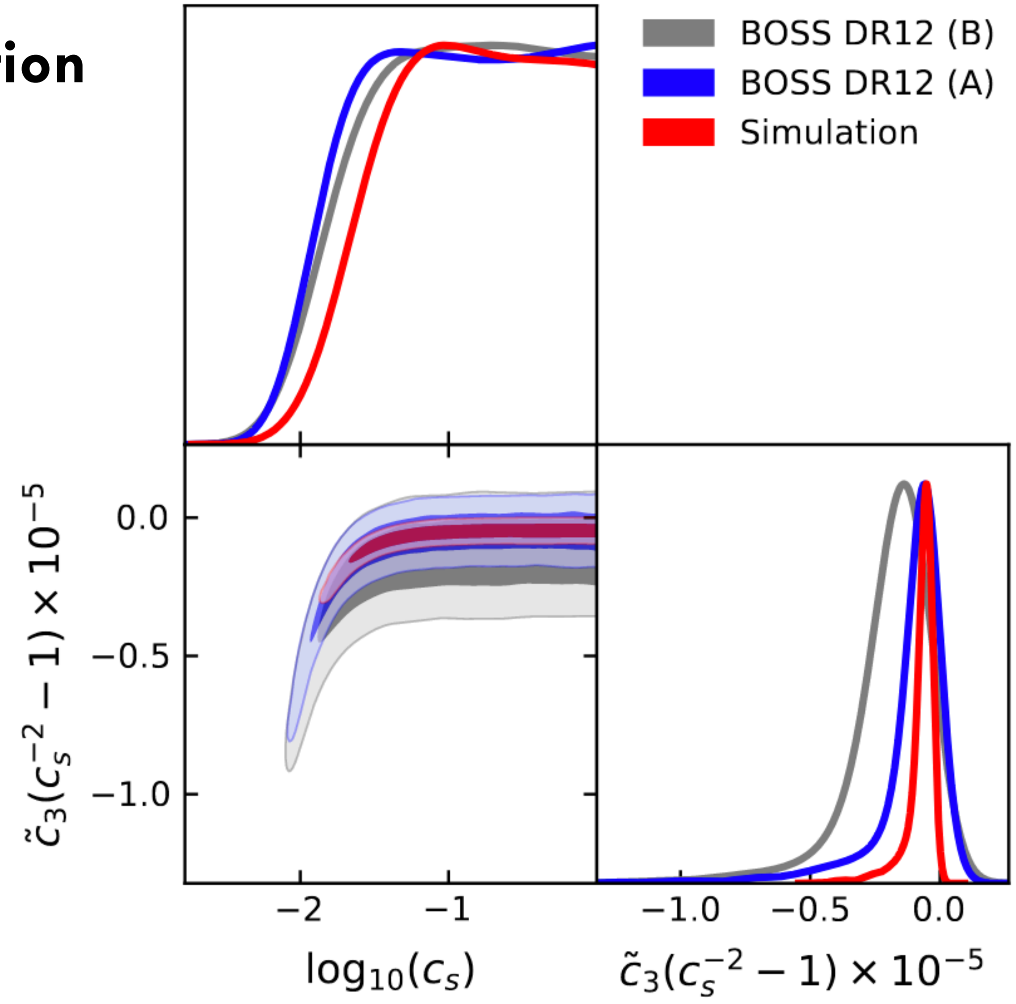
We can relate $f_{\rm NL}$ to the **couplings** in the **EFT of Inflation**

Most general 3rd order single-field action:

$$S_{\rm EFT} = \int \mathrm{d}^4x\sqrt{-g}\left[-\frac{M_{\rm P}^2\dot{H}}{c_s^2}\left(\dot{\pi}^2 - c_s^2\frac{(\boldsymbol{\nabla}\pi)^2}{a^2}\right) + \frac{M_{\rm P}^2\dot{H}}{c_s^2}(1-c_s^2)\left(\frac{\dot{\pi}(\boldsymbol{\nabla}\pi)^2}{a^2} - \left(1+\frac{2}{3}\frac{\tilde{c}_3}{c_s^2}\right)\dot{\pi}^3\right)\right]$$

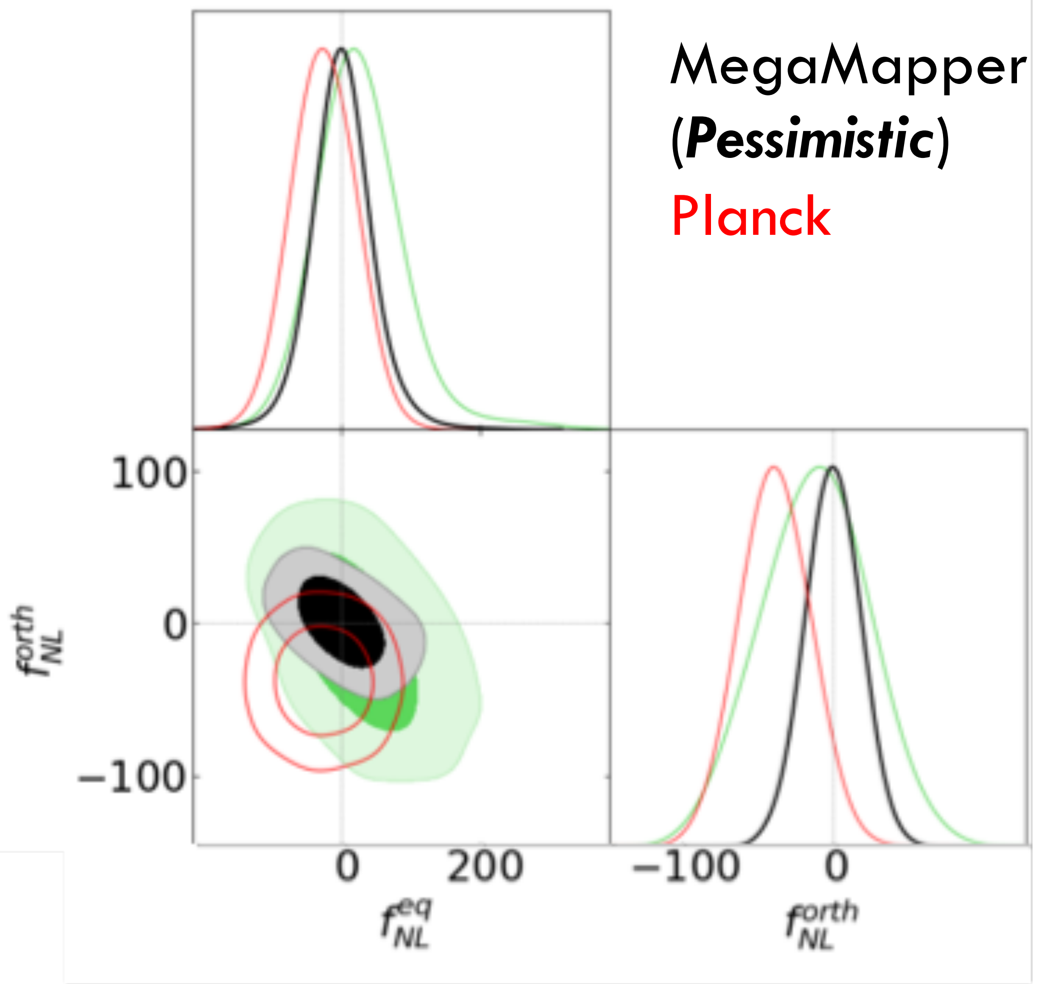
We find $c_s^2 \geq 0.013$ at 95% CL

See Ana's talk!



Senatore+09, Cabass+21

FUTURE PROSPECTS



- MegaMapper gets **better** non-local PNG constraints than *Planck*
- **Actual** constraints will use **higher** $k_{\max}$:
  - Higher redshift
  - Better modelling

Cabass+21,22 (see also d'Amico+22)

OTHER IDEAS: BEYOND PERTURBATION THEORY

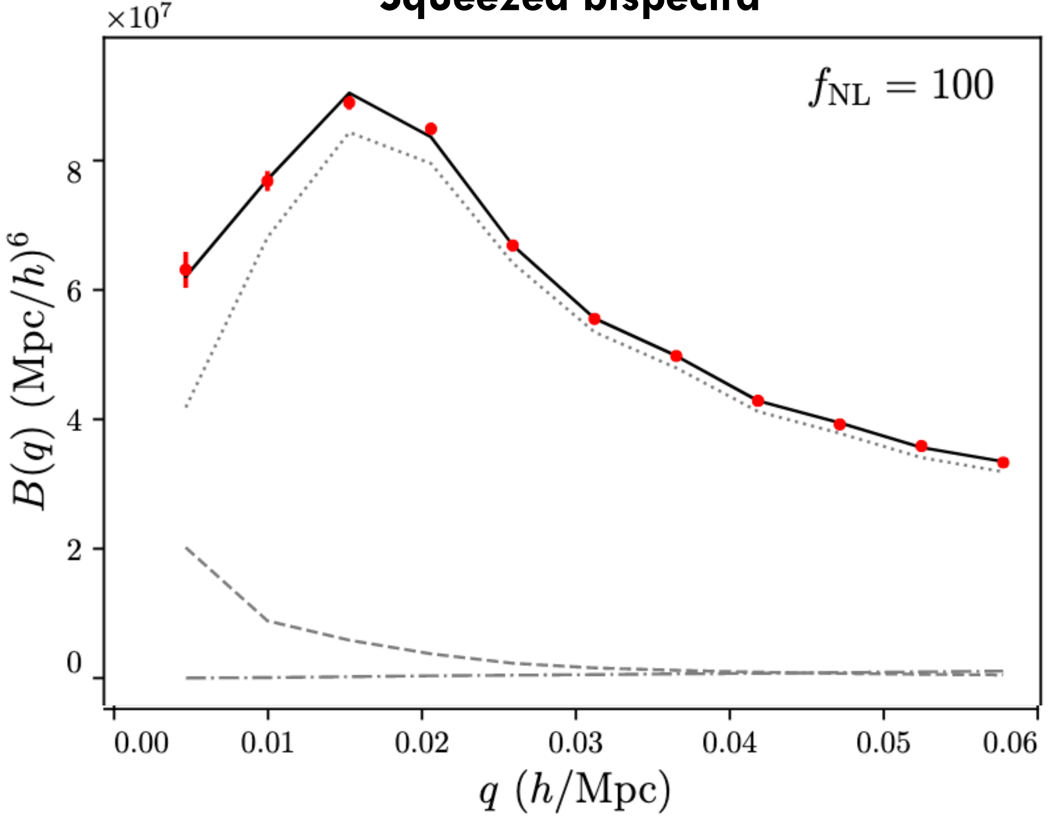
Sam Goldstein

- We can measure **local** f_{NL} from the **non-linear** bispectrum using **consistency relations**

$$B(\boldsymbol{q},\boldsymbol{k}) = \frac{6 f_{\mathrm{NL}} \Omega_{m,0} H_0^2}{D_{\mathrm{md}}(z)} \frac{\partial P(k)}{\partial \log \sigma_8^2} \frac{P(q)}{q^2 T(q)} + \mathcal{O}(f_{\mathrm{NL}}^2)$$

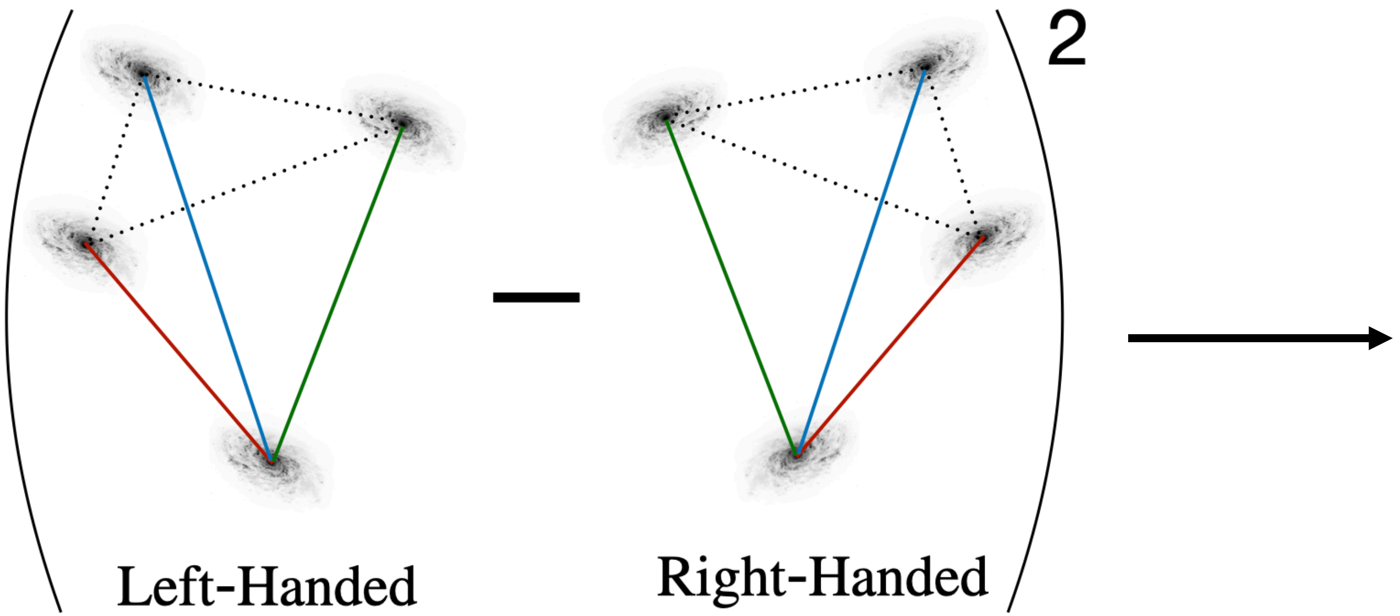
- This gives **accurate** $f_{\mathrm{NL}}^{\mathrm{loc}}$ constraints for matter at $k = 0.6h/\mathrm{Mpc}$

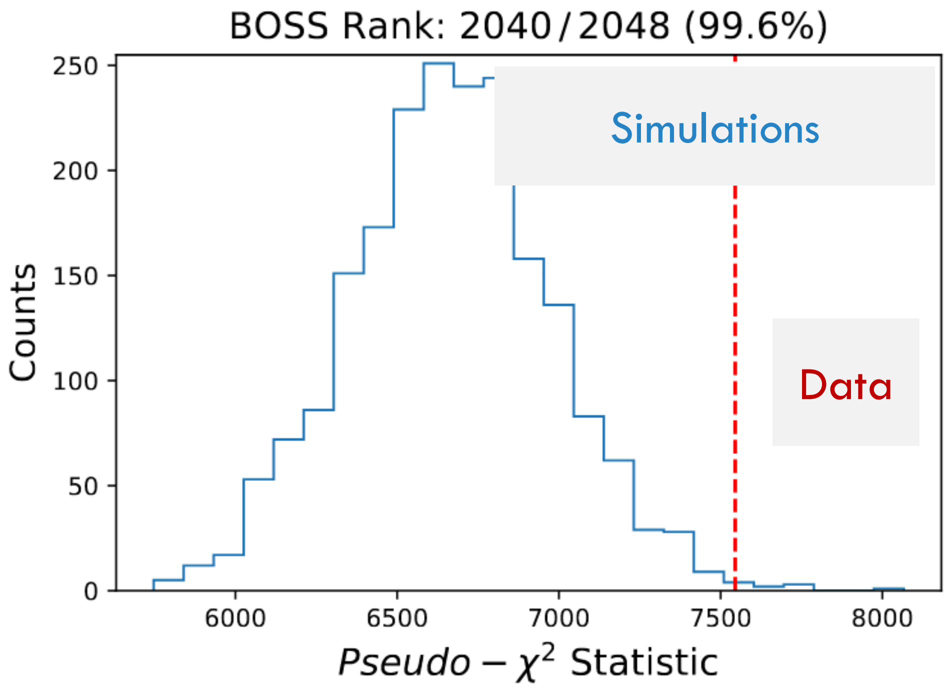
Squeezed bispectra



Goldstein+22

OTHER IDEAS: PARITY-ODD 4-POINT FUNCTIONS



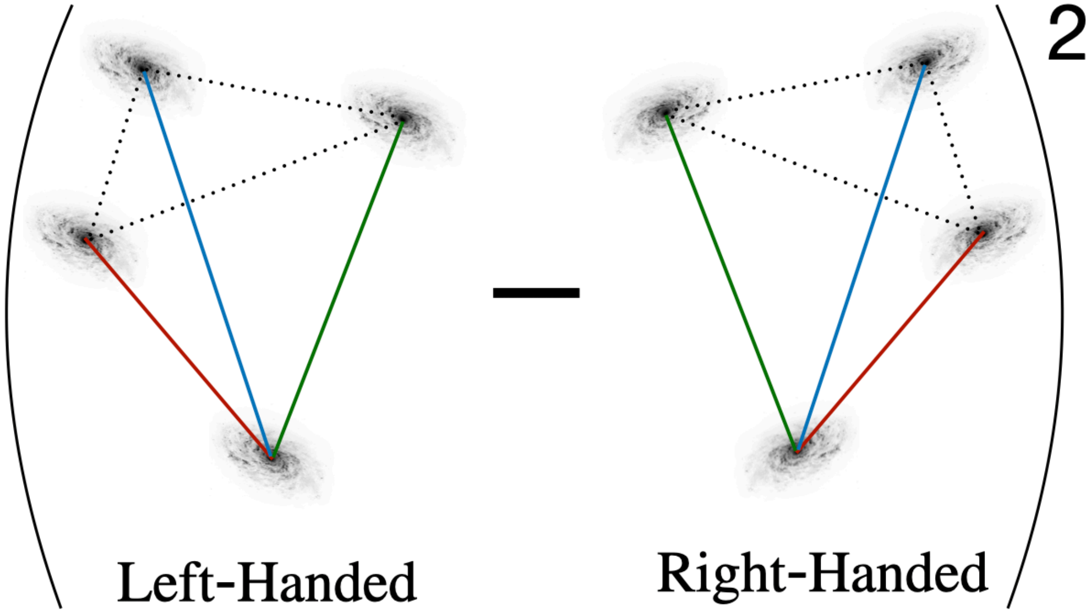


Conclusions

- Simulations do not capture noise properties of the data
- **<u>Or</u>** we have detected *parity-violating inflation* at 3σ???

Philcox 22

BONUS: PARITY-ODD 4-POINT FUNCTIONS



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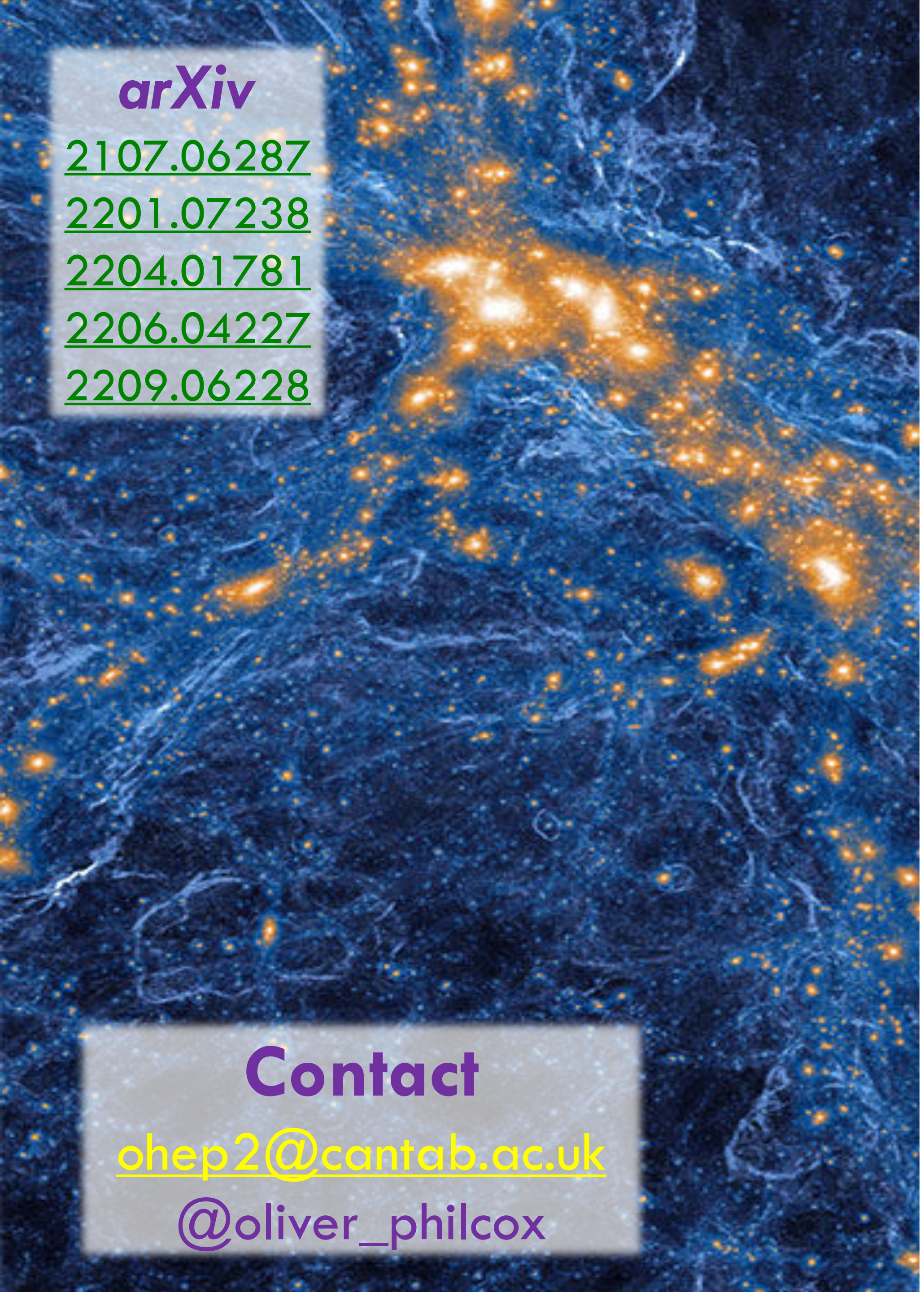
The universe is surprisingly lopsided and we don't know why

Two analyses of a million galaxies show that their distribution may not be symmetrical, which may mean that our understandings of gravity and the early universe are incorrect

Conclusions

- Simulations do not capture noise properties of the data
- **Or** we have detected *parity-violating inflation* at 3σ???

Philcox 22



CONCLUSIONS

- We can measure **any** type of 3-point PNG using the galaxy **power spectrum** and **bispectrum**
- Constraints are **weak** compared to the CMB but will get much stronger soon!
- We can learn more from non-perturbative physics and higher-point functions!